Final Progress Report

Earthquake Hazards Program Assistance Awards

July 9, 2018

- **USGS Award Number**: G15AC00202
- **Title of award**: Extension of the ISC-GEM Global Instrumental Earthquake Catalogue (Years 2-4)
- **Author(s) and Affiliation(s)**: Dmitry A. Storchak, International Seismological Centre, Pipers Lane, Thatcham, Berkshire, RG19 4NS, United Kingdom, Phone: +44 1635 861022, Fax: +44 1635 872351, dmitry@isc.ac.uk
- **Term covered by the report**: 06/22/2017 through 06/21/2018
- **Funding expended for the term covered by the report**: The expenditure on this project is equal to the cost of time of the IT and Data Entry personnel. At the end of the project year, the incurred expenditure amounted to $76,815. This amount is higher than originally budgeted almost four years ago. It is subject to the inflationary adjustments made to the ISC Salary Scales, length-of-service adjustments for ISC staff pensions and US dollar to UK sterling exchange rate. The following table provides further details.

  Despite the overspending, we claimed and received from USGS the originally budgeted amount of **$71,687**. We are truly grateful for this support from USGS.

Position	*Spinal point on the ISC Salary Scales*	*Per annum, £*	*Per annum, $*	*% of full time*	*Cost, $*	*Statutory (*) contributions, $*	*Total, $*
IT	*Grade 09S Point 48*	*55,948*	*74,635*	*25*	*18,659*	*7,841*	*26,500*
Data Entry	*Grade 05S Point 25*	*27,631*	*36,860*	*50*	*18,430*	*2,442*	*20,872*
Data Entry	*Grade 03S Point 12*	*19,489*	*25,998*	*100*	*25,998*	*3,445*	*29,443*
				Total, $	*63,087*	*13,728*	***76,815***

* *Statutory contribution* is the ISC contribution to the UK National Insurance scheme and a pension fund where applicable.

The ISC Salary Scales are updated in January of each year based on the CPI index published by the UK Office of National Statistics and formally approved by the Chair of the ISC Governing Council and the Chair of the ISC Executive Committee.

- **Report body:**

Objectives of the 4th Year of the Extension Project

Objectives of the 4th Year of the ISC-GEM Extension project were to process:

- earthquakes during 1904-1919 with phase data listed in various sources and with magnitudes between 5.5 and 7.5, i.e. earthquakes not included in the original ISC-GEM catalogue (see Storchak *et al*., 2013);
- earthquakes down to magnitude 5.5 that occurred in 2014 based on the newly available data from the ISC Bulletin.

Status of the ISC-GEM catalogue before the works have begun

The state of the ISC-GEM catalogue for the period 1904-1919 (Version 4.00, dated 26 January 2017) reflected the cut-off magnitude 7.5 adopted for the first release of the ISC-GEM catalogue in 2012 (Table I). Earthquakes listed in the supplementary catalogue either have a poorly constrained location or (more often) no moment magnitude estimate.

Table I*: the original number of earthquakes during 1904-1919 (in both the main and the supplementary ISC-GEM catalogues) with cut-off magnitude 7.5:*

Year	Number of earthquakes in the main catalogue	Number of earthquakes in the supplementary catalogue
1904	1	3
1905	5	5
1906	4	7
1907	4	1
1908	3	4
1909	4	4
1910	4	2
1911	10	2
1912	2	3
1913	7	1
1914	6	2
1915	8	1
1916	7	1
1917	8	4
1918	32	13
1919	25	7
Total	**130**	**60**

At the end of the project Year 3, earthquake data in the catalogue terminated at the end of year 2013.

Collecting data for earthquakes during 1904-1919

The extension of the catalogue for earthquakes that occurred during 1904-1919 with magnitude below 7.5 started in December 2016. In order to perform the relocation and magnitude re-computation of earthquakes, we needed to digitize body-wave arrival times as well as amplitudes and periods of various phases using a multitude of sources.

Earthquake selection and phase data collection

For this time period we have used several data sources for collecting phase arrival times necessary for the relocation. Figure 1 summarizes the number of known earthquakes and station data sources used in different years. There is a notable increase in the number of events from year 1917 (last year of the BAAS) before the beginning of the ISS bulletin in 1918. Note also the significant drop of earthquakes in 1908, coinciding with the end of the ISA bulletins (see Schweitzer and Lee, 2002, and references therein).

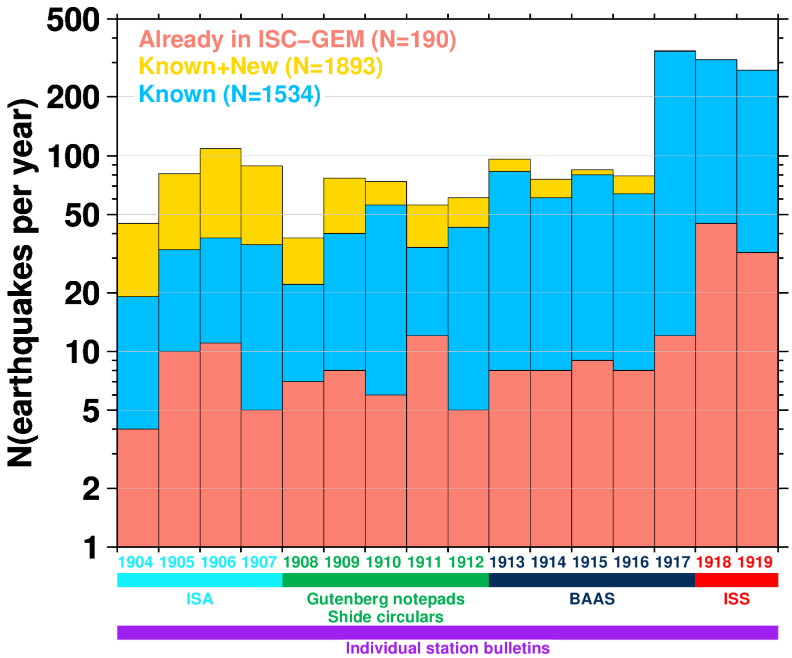

Fig. 1: *Annual number of (known) events per year during 1904-1919: red = already in the ISC-GEM main catalogue; blue = all known earthquakes in the ISC Bulletin (including the Centennial Catalogue by Engdahl and Villaseñor, 2002); yellow = new earthquakes added to the ISC Bulletin from various sources. The phase data sources used for different time periods are also shown.*

Not all the earthquakes summarized in Figure 1 are large enough to be included in the ISC-GEM catalogue. However, to be as comprehensive as possible, we digitized all station data available to us for each event, even if the earthquake was likely to be below 5.5. At the end of the data collection (see Di Giacomo et al., 2015a), we have discarded ~830 earthquakes with poor station coverage or no data available at all. Out of the remaining events we have relocated 1,111 earthquakes that occurred between 1904 and

1919. Table II summarizes the annual number of the relocated earthquakes per year along with the phase data availability.

***Table II**: annual number of relocated earthquakes and the summary of the phase data (stations) for each year.*

Year	Number of relocated earthquakes	Number of phases (stations)
1904	27	968 (84)
1905	68	2412 (115)
1906	80	2599 (111)
1907	81	3663 (107)
1908	28	755 (75)
1909	44	792 (66)
1910	53	1302 (74)
1911	39	1143 (94)
1912	49	1358 (94)
1913	78	4239 (88)
1914	61	2912 (90)
1915	77	3130 (71)
1916	66	2629 (77)
1917	152	4412 (80)
1918	114	3528 (97)
1919	94	2937 (97

Figure 2 shows the geographical distribution of stations used for relocation of selected earthquakes. Notably, there is much stronger contribution of readings from European stations during this period.

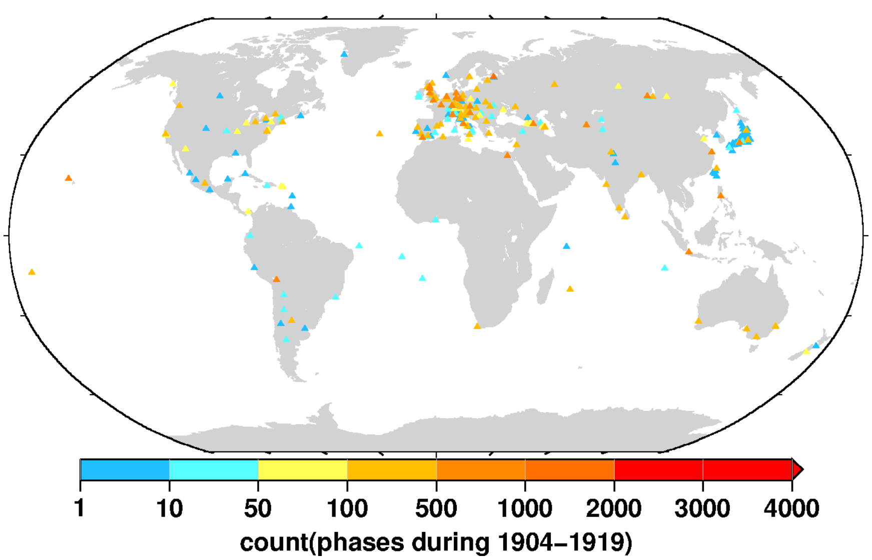

***Fig. 2:** Geographical distribution of seismic stations with phase data digitized from various sources (see Figure 1) during 1904-1919 colour-coded by the overall number of phases available.*

Amplitude-period data collection

Because most of the various sources of phase data (see Figure 1) do not list the necessary amplitude/period information to re-compute M_S , the amplitude-period data collection was done based on the original station/network bulletins (more details in Storchak *et al.*, 2013; Di Giacomo *et al.*, 2015a).

The amplitude-period data collection task benefitted from those station bulletins received from the personal collection of late professor Ambraseys and those kindly provided by the Geophysical Survey of the Russian Academy of Sciences in Obninsk (Russia), British Geological Survey (UK), geophysical Institute in Prague (Czech Republic) and University of Strasbourg (France). The bulletins from these collections helped filling some significant gaps in the original ISC collection. Similarly to Table II, the amplitude-period collection for the relocated events is summarized in Table III.

Table III: *summary of the amplitude-period data collected from station/network bulletins for earthquakes during the 1904-1919 period.*

Year	Number of amplitudes and period pairs (stations)
1904	275 (4)
1905	1217 (7)
1906	1568 (9)
1907	1879 (11)
1908	1383 (18)
1909	2618 (23)
1910	3759 (26)
1911	2111 (31)
1912	4226 (42)
1913	6799 (46)
1914	5674 (49)
1915	6646 (47)
1916	3954 (43)
1917	4091 (32)
1918	1907 (28)
1919	1473 (24)

Figure 3 shows the spatial distribution of the stations color-coded by number of readings for which we have added amplitude-period data for magnitude re-computation during 1904-1919. Notably, there is much higher contribution of amplitude/period data from stations in Europe as compared to other continents.

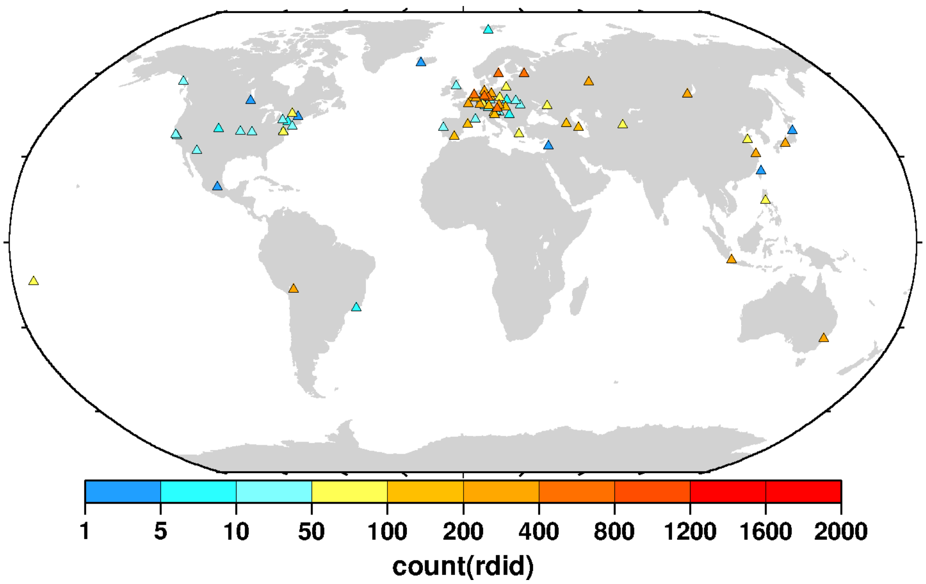

***Fig. 3**: Stations that contributed the amplitude-period data for magnitude re-computation during the period 1904-1919; stations are color-coded according to the number of readings.*

Data for earthquakes that occurred in 2014

To extend the ISC-GEM catalogue for 2014, we have taken advantage of the data that recently became available in the ISC Bulletin (www.isc.ac.uk/iscbulletin). As usual for the ISC-GEM catalogue of recent years, we selected all earthquakes with Mw(GCMT) ≥ 5.5 and added earthquakes without direct Mw from the GCMT where the Mw proxy is larger than 5.5. The Mw proxies are obtained with the same conversion relationships developed by Di Giacomo *et al.* (2015b) using as a basis the MS or mb determined by the ISC. The computation of Mw proxies was required for 35 earthquakes where the GCMT solution was not available. In total, we selected 521 earthquakes.

Earthquake relocation

As always throughout the ISC-GEM catalogue, we used the same two-tier location approach described in Bondár *et al.* (2015) to relocate the selected earthquakes during 1904-1919 and 2014. Here we only note that in the first step of the relocation procedure the depth is determined using the EHB technique (Engdahl *et al.*, 1998) and then the ISC locator (Bondár and Storchak, 2011) is used to constrain each epicentre by fixing the depth to the value obtained from the EHB processing. The ISC locator attempts to obtain an independent free-depth solution if sufficient depth resolution is available. This way we were able to crosscheck the results of two approaches and investigate cases with large discrepancies. Both the EHB and the ISC locator algorithms use all IASPEI standard phases (Storchak *et al.*, 2003 and 2011) with valid ak135 (Kennett *et al.*, 1995) 1D travel-time predictions, along with elevation, ellipticity (Dziewonski and Gilbert, 1976; Kennett and Gudmundsson, 1996; Engdahl *et al.*, 1998) and depth-phase bounce point corrections (Engdahl *et al.*, 1998).

Figure 4 shows the box-and-whisker plots of the number of stations / defining stations (i.e. stations contributing defining phases to the location) and the secondary azimuthal gap during 1904-1919 and 2014. Note the different scale in Figure 4a for 1904-1919 and 2014.

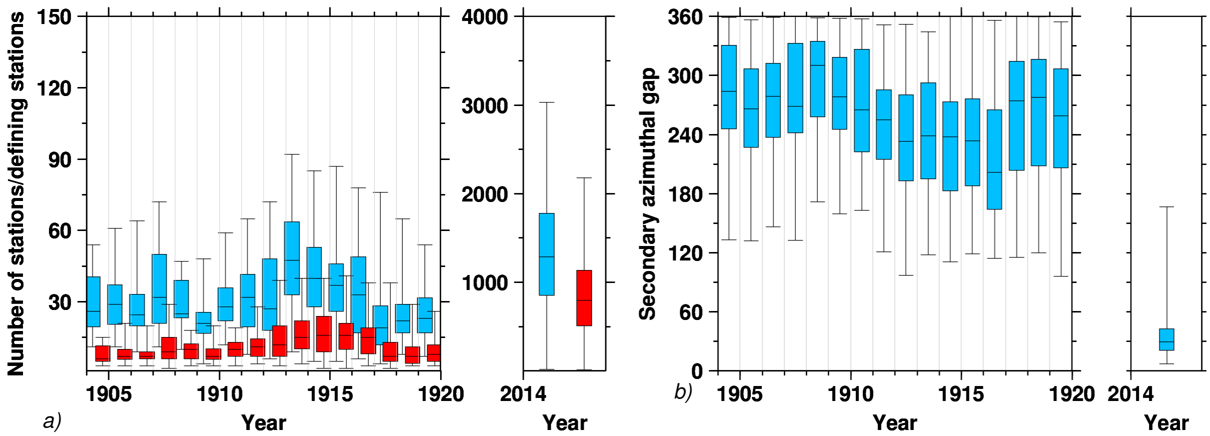

Fig. 4*: Box-and-whisker plots of a) the annual number of stations (blue) and defining stations (red), and b) the secondary azimuthal gap; boxes represent the 25% - 75 % quartile ranges, black lines represent the full, minimum to maximum range.*

Obviously, with a much larger number of stations available for 2014 the median secondary azimuthal gap is significantly smaller than during 1904-1919. Due to the small number of defining stations, we assigned location flag "D" to 245 earthquakes. Those earthquakes have been downgraded to the Supplementary catalogue.

Figure 5 shows the global maps of the previous prime (various authors and agencies for 1904-1919) / ISC locations (2014) (*"before"*) and the ISC-GEM relocations (*"after"*) for the processed earthquakes.

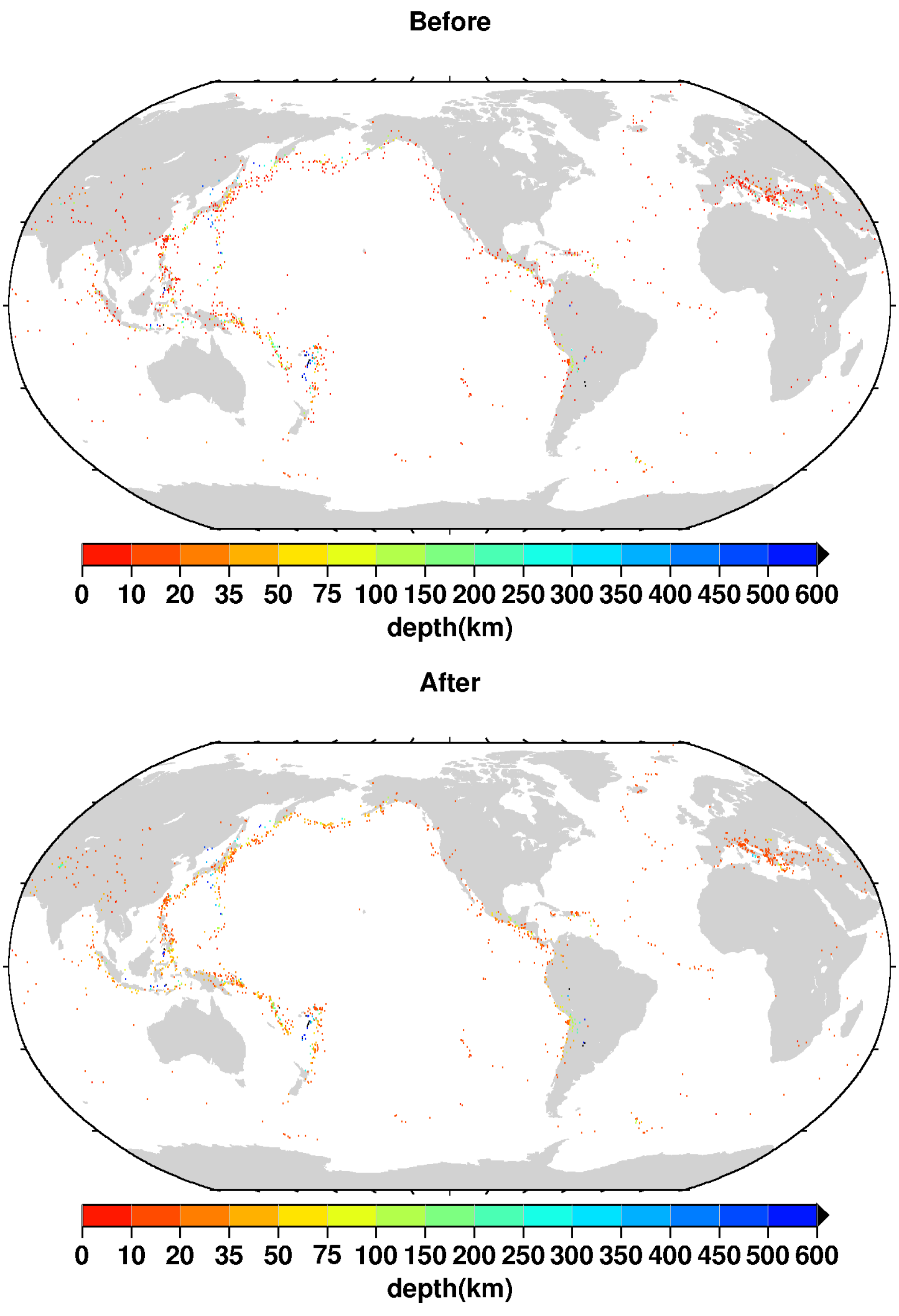

Fig. 5: *Previous prime locations (before) and ISC-GEM locations (after) for the earthquakes processed during 1904-1919 and 2014.*

Due to the small number of stations constraining epicentres during 1904-1919, we expect large differences between *before* and *after* locations as compared to more modern periods. Figure 6 and 7 show the box-and-whisker plots of the epicentral and depth differences, respectively, for each year. Note the different scale in Figure 6 for 1904-1919 and 2014.

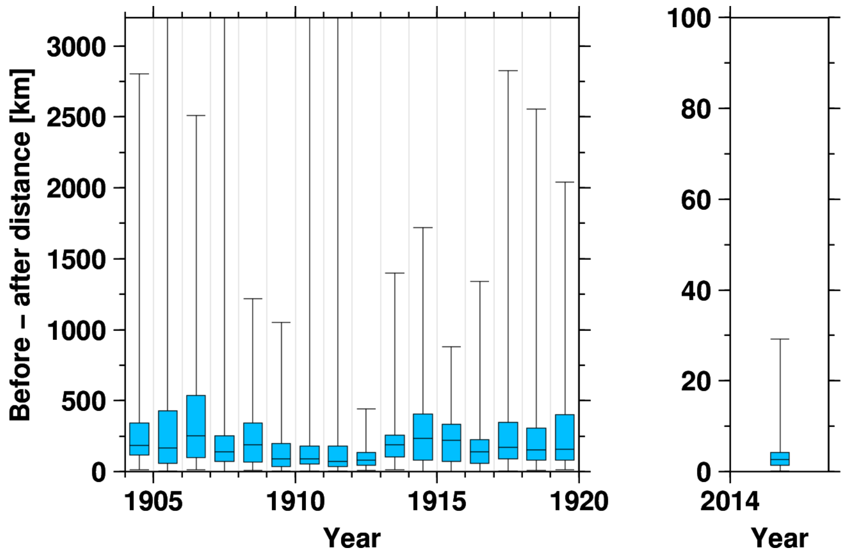

Fig. 6: *Box-and-whisker plot of the location differences before and after the ISC-GEM relocations in each year.*

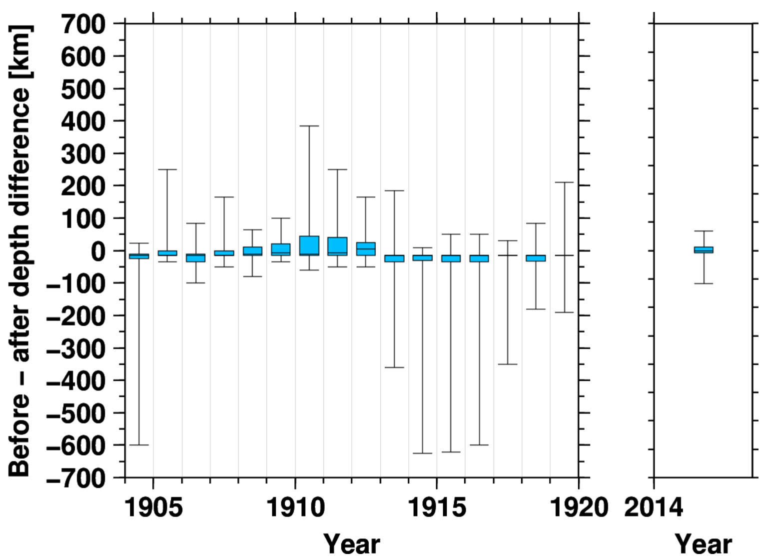

Fig. 7: *Box-and-whisker plot of the depth differences before and after the ISC-GEM relocations in each year.*

As expected, the differences between ISC/ISC-GEM locations for 2014 are small. Instead, the differences between previous primes/ISC-GEM locations in the 1904-1919 period can be significant. In particular, the largest differences (14 events with before-after distance above 1000 km) are for events in which previous primes were based on just a few stations. Most of those events have location flag "D".

Magnitude re-assessment

Magnitude re-assessment of earthquakes that occurred during 1904-1919

The magnitude re-computation of the earthquakes during 1904-1919 is one of the most important tasks of the project. Indeed, for about 58% of the 1,111 relocated earthquakes during 1904-1919 we did not have any magnitude information electronically available in the ISC database, and if any available, it is often of unknown type or obtained with undocumented procedures. Therefore, a systematic magnitude re-assessment (particularly MS) is fundamental for this period. This task could only be performed based on the amplitude-period data collected during this project (see Figure 3).

We followed the same procedures described by Di Giacomo *et al.* (2015b). Due to the lack of reliable short-period measurements in this period, we could not obtain any mb. Thus, we focus this section on the re-computed MS. Figure 8 shows the timeline of the re-computed MS during the 1904-1919. We accepted 927 MS values after checking the station magnitude distribution for each re-computed MS and cross-checked our results with other magnitude information if it was available. Note that for year 1904 we could add only three reliable MS values for the newly relocated earthquakes.

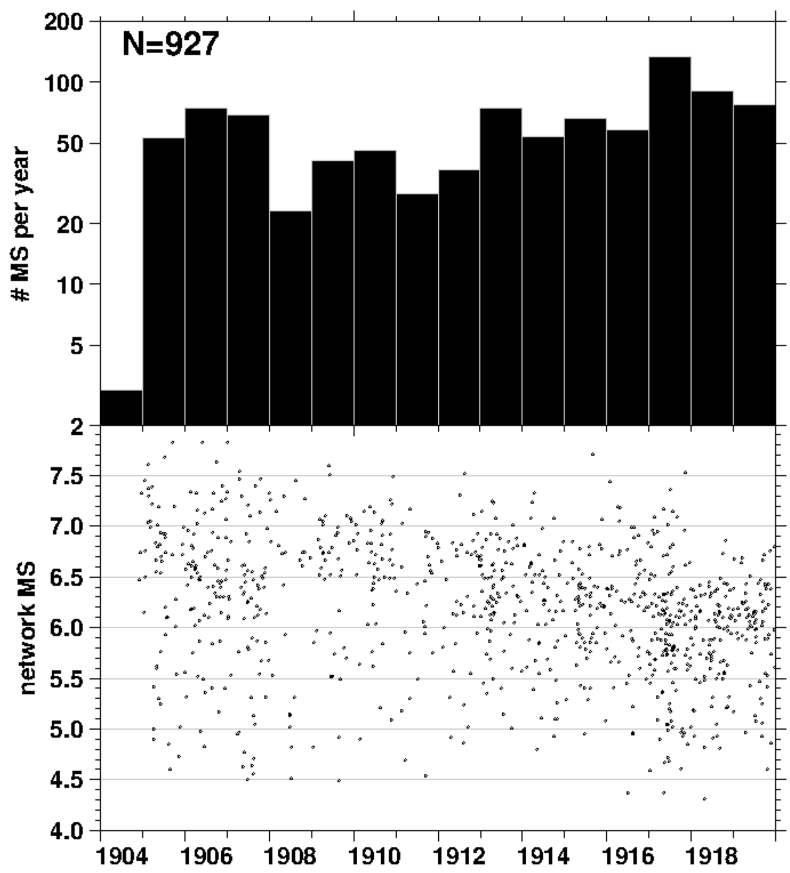

Fig. 8*: Timeline of the re-computed MS (bottom) and number of MS per year (top).*

The variation in the number of MS per year is related to the variations of the number of earthquakes during this time period (see Figure 1) and the number of stations contributing to MS (see Table III). As in other time periods studied before, an important feature of Figure 8 is the presence of earthquakes with MS < 5.5. Figure 9 shows the spatial distribution of the re-computed MS and it is possible to notice how earthquakes with MS < 5.5 are focused in areas with more stations contributing to MS (e.g., Europe, see Figure 3). We processed these earthquakes because of either poor or absent magnitude information before the project start. That led us to adopt a more conservative approach in order to process all earthquakes potentially relevant to the ISC-GEM catalogue. Such smaller earthquakes would not normally be part of the ISC-GEM catalogue. However, considering the difficulty and large manual efforts associated with re-assessing the magnitudes of past earthquakes, we included such smaller earthquakes in the Supplementary catalogue, similar as we did for the 1920-1959 period.

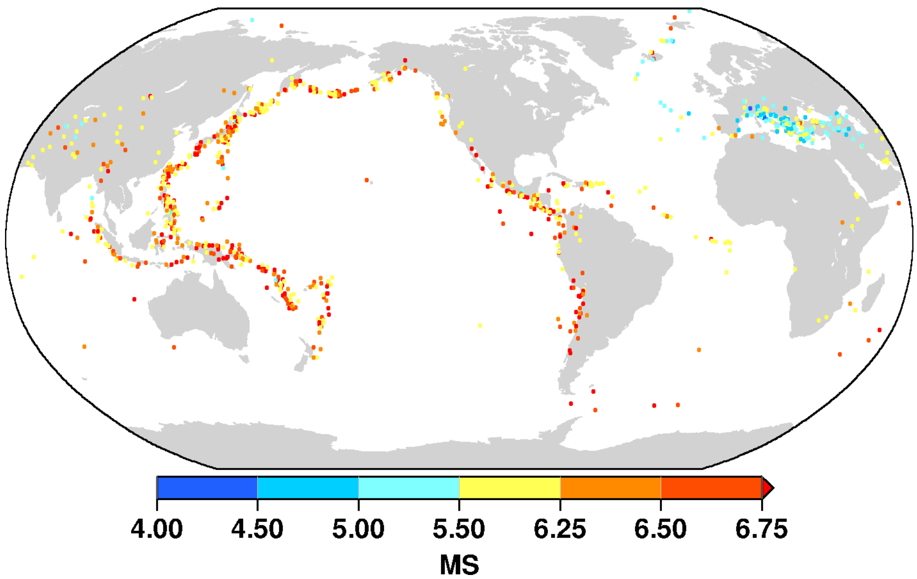

Fig. 9: *Map showing the relocated earthquakes during 1904-1919 color-coded according to the re-computed MS. Note how most of the MS < 5.5 earthquakes are located in the Euro-Mediterranean area; this generally matches the area where most of the seismic stations that contributed data for MS are positioned.*

These re-computed MS are the basis for all Mw proxies during 1904-1919.

1904-1919 earthquakes without re-computed magnitudes

Despite the effort to identify all available amplitudes and periods in various station bulletins, 184 of the relocated earthquakes during 1904-1919 had to be left with no re-computed magnitude. Figure 10 shows the timeline of these earthquakes as a function of depth. All these earthquakes, therefore, will be listed in the Supplementary Catalogue. About 50% of these earthquakes are shallow (depth ≤ 50 km). The spatial distribution of these earthquakes is shown in Figure 11.

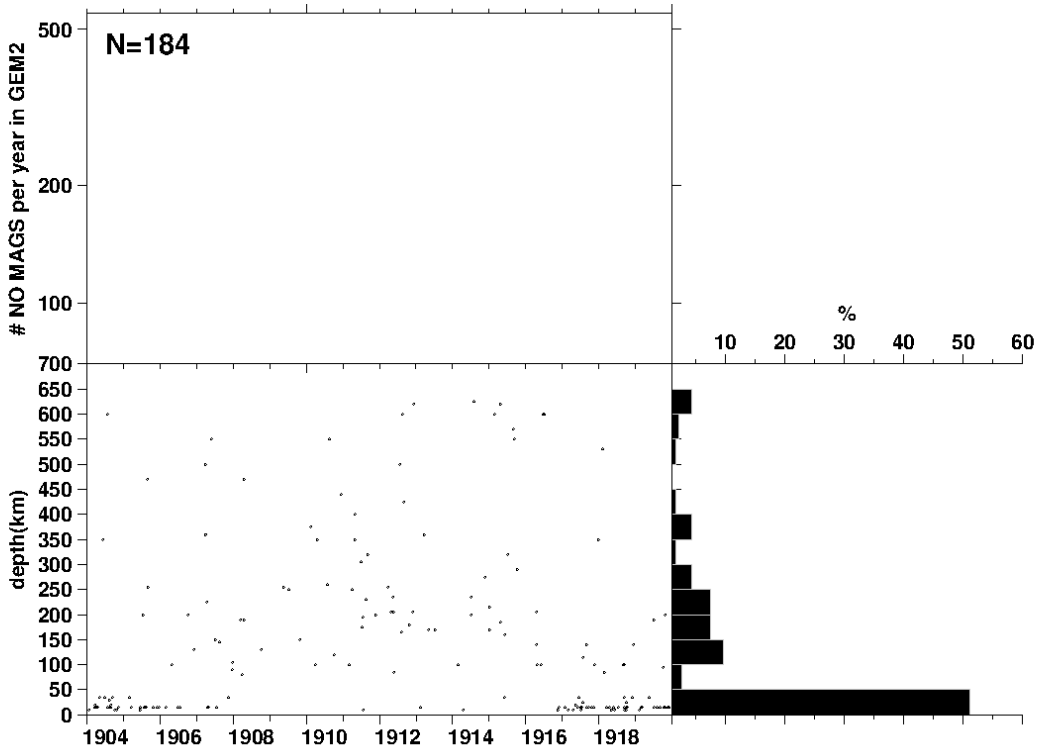

Fig. 10: *Bottom left: timeline of the depth distribution of the relocated events during the 1904-1919 period where no ISC-GEM re-computed magnitude (MS or mb) is available for consequitive Mw proxy calculation; bottom right: percentage of the earthquakes as function of depth. About 50% of the earthquakes with no re-computed magnitudes are shallow; top: annual number of relocated earthquakes with no re-computed magnitude.*

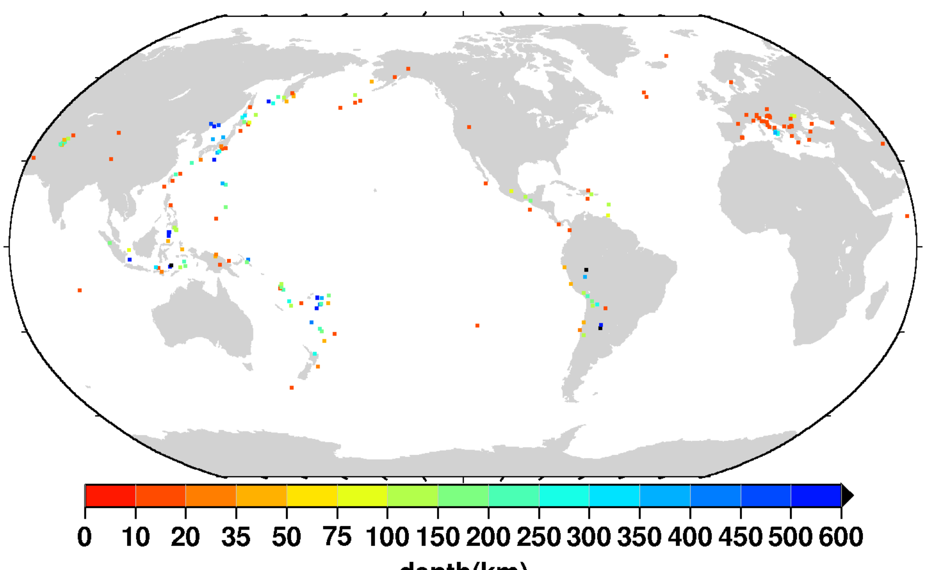

Fig. 11: *Earthquakes with no re-computed magnitude color-coded by depth.*

The shallow earthquakes with no recomputed MS are normally aftershocks of large earthquakes, earthquakes in poorly monitored areas (e.g., the South Pacific Ocean) and earthquakes not big enough for a minimum of two/three teleseismic stations to provide surface wave amplitude and period measurements. We shall revisit these earthquakes if additional printed station bulletins missing in our collection were to become available in the future.

In addition to the re-computed *MS* we also continued looking in the literature for reliable estimates of seismic moment and Mw for historical earthquakes. We added Mw for moderate events in Europe [the 1909-04-23 Benavente and the 1909-06-11 Lambesc earthquakes from Stich et al. (2005) and the two larger earthquakes of the September 1919 Torremendo, Spain, series (Batllo' et al. (2015)].

Magnitudes for earthquakes in 2014

The *Mw* from GCMT dominates the magnitude composition in the recent years. As already mentioned, we relocated 521 earthquakes in 2014 with *Mw*(GCMT) $\geq$ 5.5 and another 35 without *Mw*(GCMT). The *Mw* proxies for 35 of those earthquakes are based on *mb*. Four of them are based on *MS*. All these earthquakes have *Mw* proxy below 6.4.

Magnitude re-assessment of 1904-1919 earthquakes already in ISC-GEM

As previously mentioned, we collected stations bulletins from various sources that complemented significantly the original ISC inventory of station bulletins. On top of the extension work, therefore, we decided to add amplitude data from the newly available stations bulletins for 147 shallow earthquakes that were already available in the ISC-GEM catalogue in order to improve our re-computed MS and, as a result, the Mw proxy. Figure 12 shows the histogram distribution of the number of stations (NSTA) contributing to MS in the previous version of the ISC-GEM catalogue and to the MS obtained with the newly added amplitude data.

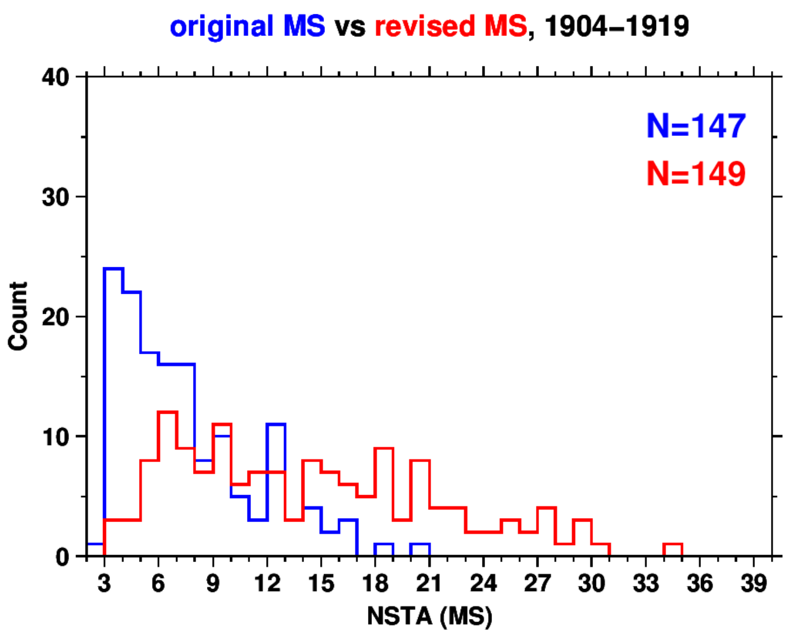

***Fig. 12**: Numbers of stations contributing to MS in the previous version of the catalogue (blue) as compared to those obtained with the newly recovered amplitude data (red).*

The increase in the number of stations (NSTA) contributing to MS is quite significant: whilst ~80% of the original MS was obtained from NSTA ≤ 10, this percentage now dropped to ~40%. In addition, new amplitude data also allowed us to gain two more MS values.

The comparison between the original and revised MS values for earthquakes in previous versions of the ISC-GEM catalogue during 1904-1917 is shown in Figure 13. The colour scale maps the increase in the number of NSTA.

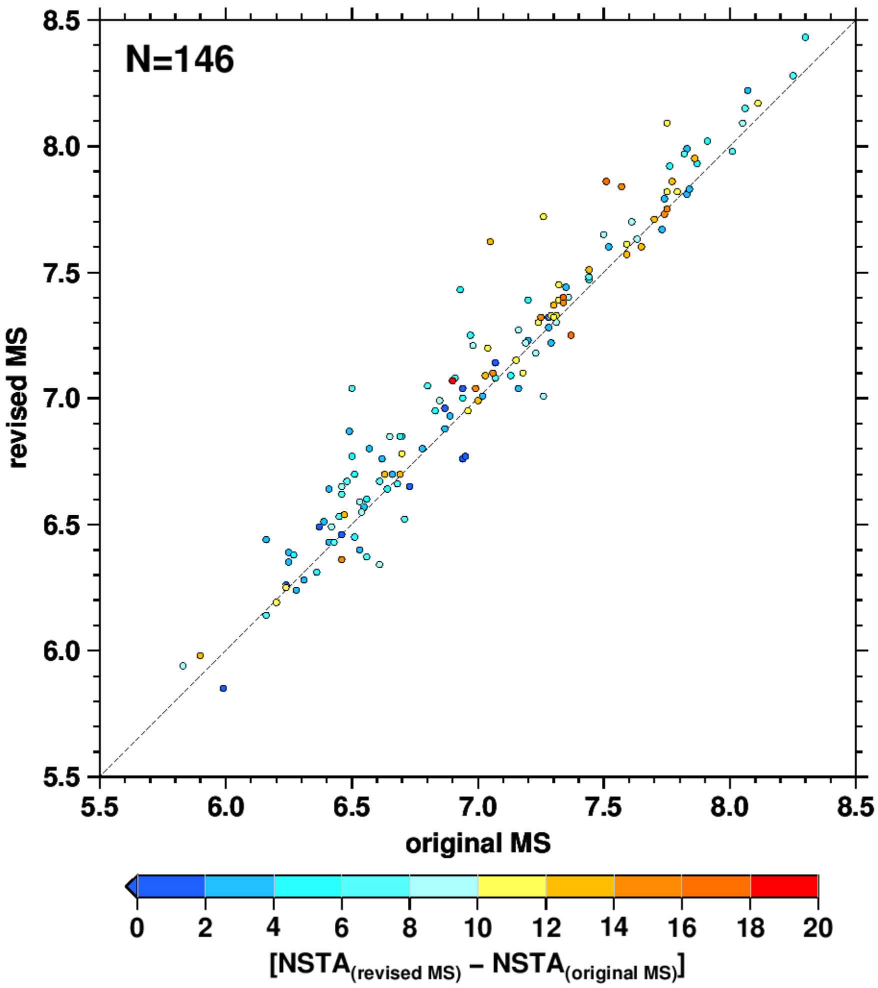

***Fig. 13**: Comparison of the original and revised MS for earthquakes during 1920-1934 that were already included in previous versions of the ISC-GEM catalogue.*

For earthquakes with MS below 6.5, the increase of NSTA is usually below 10 stations, whereas for larger magnitudes the increase in NSTA can be up to 20 stations. With the exception of few large differences, the fit is quite good considering the small NSTA available for the original MS. We revised all new MS values and we will use the revised MS in the new version of the ISC-GEM catalogue. The increased NSTA also affects the magnitude quality flag of those earthquakes for which MS is used as the basis for Mw proxy calculation, as reported in Table IV.

Table IV*: summary of the magnitude quality flag for the original and revised MS for those earthquakes already in the ISC-GEM catalogue where MS was used as the basis for Mw proxy calculation.*

Magnitude Quality Flag	Count (original MS)	Count (revised MS)
B	31	50
C	100	76
D	37	2

Revision of 16 earthquakes outside the period 1904-1919

As the last additional task, we update the location (and magnitude) of five earthquakes already listed in the main catalogue that occurred outside the 1904-1919 period. Details are as follows:

- Evid = 16958009 has now a direct Mw = 7.1 following the paper by Pino et al. (2000);
- Evid = 16958130, also known as the 1911 Kemin earthquake has an updated direct Mw = 8.0 following the recent paper of Kulikova and Krüger (2015). Also the location has been updated after adding several phase readings;
- Evid = 907513, also known as the 1930 Irpinia earthquake has a direct Mw = 6.64 following the paper of Pino et al. (2008);
- Evid = 902493 has an updated location which fits better the tsunami generation;
- Evid = 722344, also known as the 1975 Hilo, Hawaii, earthquake has an updated direct Mw = 7.7 following the more recent paper of Nettles and Ekström (2004);
- Deleted event 650848;

New version of the ISC-GEM catalogue

The updated plot of the time-magnitude distribution of the ISC-GEM main catalogue 1900-2014 is shown in Figure 14 (for comparison with previous version see Figure 20 of Di Giacomo *et al.*, 2015b).

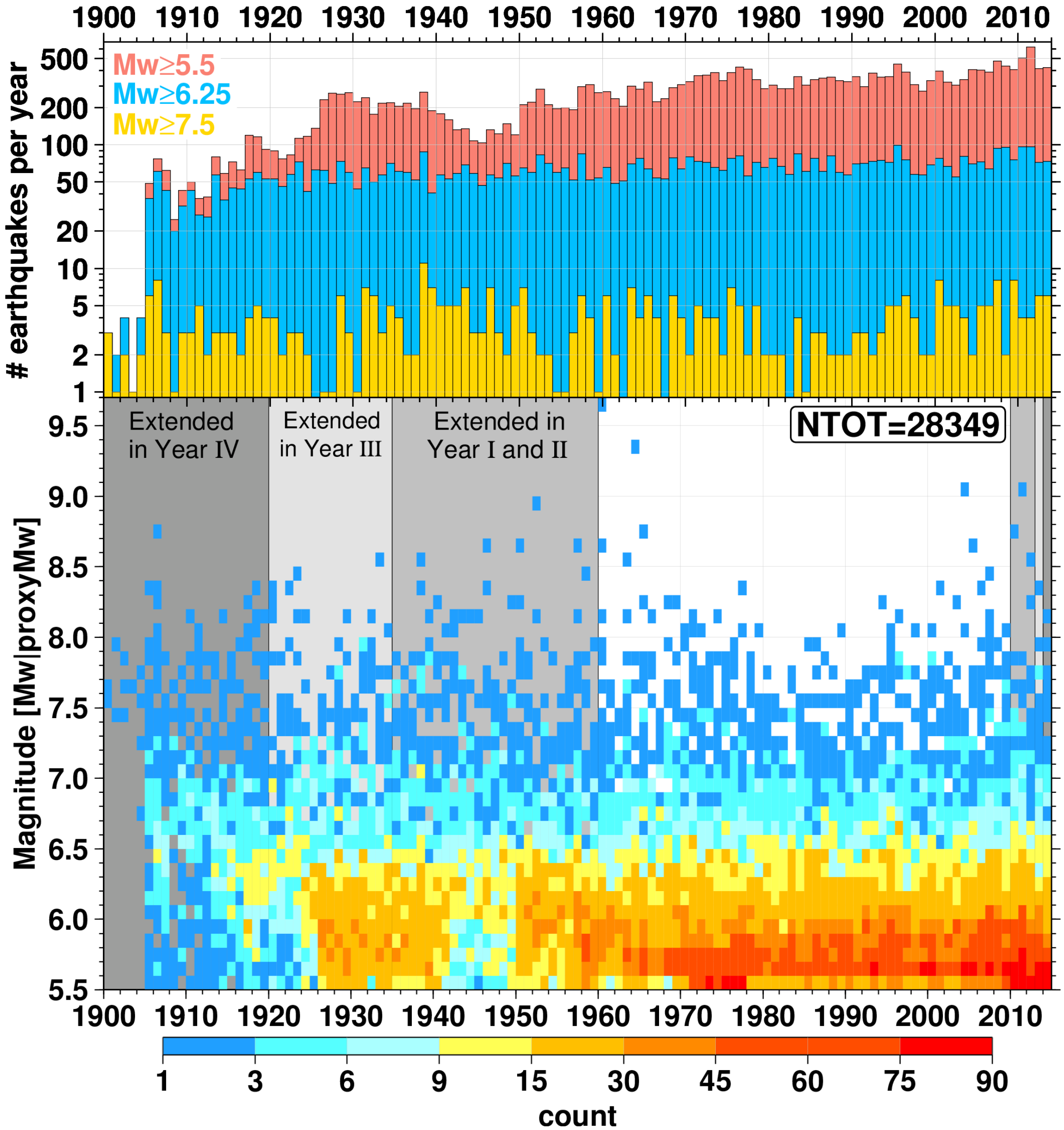

Fig. 14: *Top: cumulative annual number of earthquakes with Mw ≥ 5.5 (red), ≥ 6.5 (blue) and ≥ 7.5 (yellow); Bottom: time-magnitude distribution color-coded in cells of 0.1 Mw units for each year of the ISC-GEM catalogue. Note that in this plot also included are the magnitudes (unless magnitude flag = "D") of events with location flag "D" (i.e., events in the Supplementary Catalogue). The shaded grey areas highlight the time-periods dealt with during the previous years of the Extension project.*

The earthquakes that occurred in 2014 extend the same magnitude distribution that we can observe in recent years and add significant earthquakes to the catalogue. The biggest difference with the previous version is in the pre-1920 period, where nearly no earthquakes below 6.5 were previously listed. Both the time-frequency distribution and the annual number of events per year above 5.5 show, however, that during the 1904-

1919 period the ISC-GEM catalogue is not as complete as in the more recent decades, especially for the years 1908-1912.

Conclusions

During the 4th year of the ISC-GEM Extension project we relocated 1,110 earthquakes that occurred between 1904 and 1919 and 521 large global earthquakes in 2014. For 246 of them we assigned poor location quality (i.e., those events are listed in the Supplementary catalogue). We were not able to re-compute reliable magnitudes of 184 earthquakes.

The relocation and magnitude re-computation were possible thanks to the digitization of the multiple sources of body wave arrival times and amplitudes and periods of surface waves from printed station bulletins. In addition, we also improved the MS estimations for 149 earthquakes already listed in the ISC-GEM catalogue during 1904-1919 by using the newly acquired station bulletins kindly provided from the personal collection of N. Ambraseys, British Geological Survey (BGS), Geophysical Institute of the Czech Academy of Sciences in Prague (Czech Republic), Geophysical Survey of the Russian Academy of Science in Obninsk (Russia) and the University of Strasbourg (France).

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- **Investigations undertaken**:
  - Digitizing of paper-based historical documents available at the ISC and several other institutions to obtain relevant arrival times and amplitudes and periods of body and surface waves from individual historical seismic observatory bulletins
  - Loading into the database, associating per physical event
  - Re-computation of locations and magnitudes
  - Checking and validation
- **Accomplishments at the end of Year 4 that marks the end of Extension project**:
  - The ISC-GEM Global Instrumental Earthquake Catalogue was extended with a total of ~1,100 known earthquakes during 1904-1919 and 521 earthquakes with magnitude 5.5 and above in 2014.
  - The hypocentres and magnitudes of the added earthquakes have been recomputed based on the instrumental data and the same advanced techniques used for preparation of the original ISC-GEM catalogue.
  - The original MS estimates for ~150 earthquakes already listed in the catalogue during 1904-1919, have been improved based on the newly acquired station bulletins.
  - Large volume of parametric seismic data was digitized from paper-based historical documents available at the ISC and several other institutions.
  - Locations and magnitudes of added earthquakes have been recomputed based on instrumental data and advanced techniques used in production of the original catalogue.
  - The ISC-GEM catalogue remains the longest and most homogeneous global source of instrumentally based earthquake parameters.
  - The catalogue download statistics and numerous scientific references in conference presentations and scientific articles demonstrate a great usefulness of the ISC-GEM catalogue to the seismic hazard and risk community.
  - The ISC-GEM Catalogue and underlying parametric seismogram measurements serve as a basis for the historical part of the *USGS ComCat catalog*.
- **Problems encountered**: No critical problems were encountered during this period.
- **Publications and/or presentations to date**:

Storchak, D.A., D. Di Giacomo, E.R. Engdahl, J. Harris, I. Bondár, W.H.K. Lee, P. Bormann and A. Villaseñor, 2015. The ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009): Introduction, *Phys. Earth Planet. Int.,* 239, 48-63, doi: 10.1016/j.pepi.2014.06.009.

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/D.A. Storchak/